21 Temperature, Heat, and Expansion

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Chapter 21 defines basics such as heat, temperature, internal energy, and specific heat. It is the foundation for the next three chapters.

The pie cools—the air warms.

All matter—solid, liquid, and gas—is composed of continually jiggling atoms or molecules. Because of this random motion, the atoms and molecules in matter have kinetic energy. The average kinetic energy of these individual particles causes an effect we can sense —warmth. Whenever something becomes warmer, the kinetic energy of its atoms or molecules has increased.

It's easy to increase the kinetic energy in matter. You can warm a penny by striking it with a hammer—the blow causes the molecules in the penny to jostle faster. If you put a flame to a liquid, the liquid also becomes warmer. Rapidly compress air in a tire pump and the air becomes warmer. When the atoms or molecules in matter move faster, the matter gets warmer. Its atoms or molecules have more kinetic energy. For brevity in this chapter, rather than saying *atoms and molecules*, we'll simply say molecules—by which we mean either.

So when you warm up by a fire on a cold winter night, you are increasing the molecular kinetic energy in your body.

Videotape: Show "Heat, Temperature, and Expansion" from the series *Conceptual Physics Alive!*

Review kinetic energy (Chapter 8).

21.1 Temperature

The quantity that tells how hot or cold something is compared with a standard is **temperature.** We express temperature by a number that corresponds to a degree mark on some chosen scale.

Nearly all matter expands when its temperature increases and contracts when its temperature decreases. A common thermometer measures temperature by showing the expansion and contraction of a liquid—usually mercury or colored alcohol—in a glass tube using a scale.

Important Terms

absolute zero
Celsius scale
Fahrenheit scale
Kelvin scale
temperature

For students who may not be familiar with Celsius temperatures, room temperature is approximately 20°C, body temperature is 37°C, and desert temperatures often exceed 40°C.

Note that absolute zero means no *available* kinetic energy.

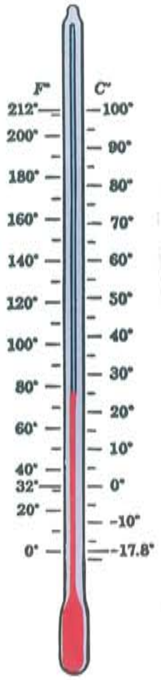

Figure 21.1 ▲
Fahrenheit and Celsius scales on a thermometer.

On the most widely used temperature scale, the international scale, the number 0 is assigned to the temperature at which water freezes, and the number 100 to the temperature at which water boils (at standard atmospheric pressure). The gap between freezing and boiling is divided into 100 equal parts, called *degrees.* This temperature scale is the **Celsius scale.***

On the temperature scale used commonly in the United States, the number 32 designates the temperature at which water freezes, and the number 212 is assigned to the temperature at which water boils. This temperature scale is called the **Fahrenheit scale.** The Fahrenheit scale will become obsolete if and when the United States goes metric.

The scale used in scientific research is the SI scale—the **Kelvin scale.** Its degrees are the same size as the Celsius degree and are called "kelvins." On the Kelvin scale, the number 0 is assigned to the lowest possible temperature—**absolute zero.** At absolute zero a substance has no kinetic energy to give up. Zero on the Kelvin scale, or absolute zero, corresponds to –273°C on the Celsius scale. We will learn more about the Kelvin scale in Chapter 24.

Arithmetic formulas can be used for converting from one temperature scale to another and are often popular in classroom exams. Such arithmetic exercises are not really physics, so we will not be concerned with them here. Besides, a conversion from Celsius to Fahrenheit, or vice versa, can be very closely approximated by simply reading the corresponding temperature from the side-by-side scales in Figure 21.1.

Temperature and Kinetic Energy

Figure 21.2 ▲
There is more molecular kinetic energy in the bucketful of warm water than in the small cupful of higher-temperature water.

Temperature is related to the random motions of the molecules in a substance. In the simplest case of an ideal gas, temperature is proportional to the *average* kinetic energy of molecular translational motion (that is, motion along a straight or curved path). In solids and liquids, where molecules are more constrained and have potential energy, temperature is more complicated. But it is still true that temperature is closely related to the average kinetic energy of translational motion of molecules. So the warmth you feel when you touch a hot surface is the kinetic energy transferred by molecules in the surface to molecules in your fingers.

Note that temperature is *not* a measure of the *total* kinetic energy of all the molecules in a substance. There is twice as much kinetic energy in 2 liters of boiling water as in 1 liter. But the temperatures of both liters of water are the same because the average kinetic energy of molecules in each is the same.

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* The Celsius scale is named in honor of the man who first suggested it, the Swedish astronomer Anders Celsius (1701–1744). It used to be called the centigrade scale, from *centi* ("hundredth") and *gradus* ("degree"). The Fahrenheit scale is named after the German physicist Gabriel Fahrenheit (1686–1736), and the Kelvin scale, after the British physicist Lord Kelvin (1824–1907).

DOING PHYSICS

Can You Trust Your Senses?

Put some hot water, warm water, and cold water in three open containers. Place a finger in the hot water and a finger of the other hand in the cold water. After a few seconds, place them both in the warm water. How do they feel? Do you see the value of a thermometer for measuring temperature?

Activity

The Best From Conceptual Physics Alive!

Demo: Low Temperatures with Liquid Nitrogen

Side 3
Chapter 1

21.2 Heat

If you touch a hot stove, energy will enter your hand from the stove because the stove is warmer than your hand. But if you touch ice, energy will pass out of your hand and into the colder ice. The direction of spontaneous energy transfer is always from a warmer substance to a cooler substance. The energy that transfers from one object to another because of a temperature difference between them is called **heat.**

It is common—but incorrect with physics types—to think that matter *contains* heat. Matter contains energy in several forms, but it does not contain heat. Heat is energy in transit from a body of higher temperature to one of lower temperature. Once transferred, the energy ceases to be heat.* In Chapter 8 we called the energy resulting from heat flow *thermal energy,* to make clear its link to heat and temperature. In this and following chapters, we will use the term that scientists prefer, *internal energy.*

When heat flows from one object or substance to another it is in contact with, the objects or substances are said to be in **thermal contact.** Given thermal contact, heat flows from the higher-temperature substance into the lower-temperature substance. However, heat will not necessarily flow from a substance with more total molecular kinetic energy to a substance with less total molecular kinetic energy. For example, there is more total molecular kinetic energy in a large bowl of warm water than there is in a red-hot thumbtack. Yet, if the tack is immersed in the water, heat does not flow from the water which has more total kinetic energy to the tack which has less. It flows from the hot tack to the cooler water. Heat flows according to temperature differences—that is, average molecular kinetic energy differences. Heat never flows on its own from a cooler substance into a hotter substance. We will return to this concept in Chapter 24 when we look at thermodynamics.

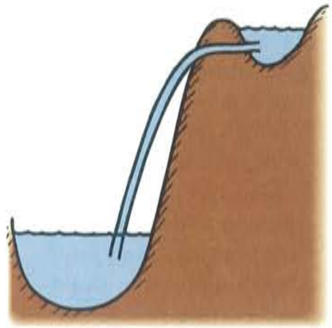


Figure 21.3 ▲
Just as water will not flow uphill by itself, regardless of the relative amounts of water in the reservoirs, heat will not flow from a cooler substance into a hotter substance by itself.

Important Terms

heat
thermal contact

Stress the irreversibility of heat flow without work input.

Emphasize that heat, like work, is energy in transit, not energy contained in a substance. The contained energy is internal energy.

* Similarly, work is also energy in transit. A body does not *contain* work. It *does* work or has work done on it.

LINK TO ENTOMOLOGY

Desert Ants

The surface temperatures of some deserts in Africa and central Asia reach 60°C (140°F). This is hot, but not too hot for a species of ant *(Cataglyphis)* that thrives at this searing temperature. These desert ants can forage for food at temperatures too high for lizards who eat them. Resilient to heat, these ants can withstand higher temperatures than any other creatures in the desert. They scavenge the desert surface for corpses of those who did not find cover in time, touching the hot sand as little as possible while often sprinting on four legs with two high in the air. Although their foraging paths zigzag over the desert floor, their return paths are almost straight lines to their nest holes. They attain speeds of 100 body lengths per second. During an average six day life, most of these ants retrieve 15 to 20 times their weight in food.

Important Term

thermal equilibrium

Important Term

internal energy

21.3 Thermal Equilibrium

After objects in thermal contact with each other reach the same temperature, no heat flows between them—we say the objects are in **thermal equilibrium.**

To read a thermometer we wait until it reaches thermal equilibrium with the substance being measured. When a thermometer is in contact with a substance, heat flows between them until they have the same temperature. We then know the temperature of the thermometer is also the temperature of the substance. So a thermometer, interestingly enough, shows only its own temperature.

A thermometer should be small enough that it does not appreciably alter the temperature of the substance being measured. If you are measuring the temperature of room air, then the heat absorbed by the thermometer will not lower the air temperature noticeably. But if you are trying to measure the temperature of a drop of water, the temperature of the drop after thermal contact may be quite different from its initial temperature.

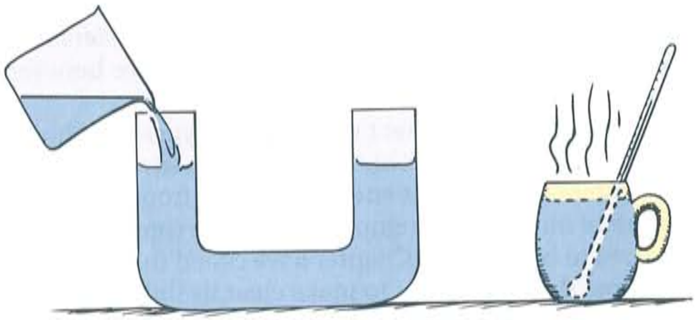


Figure 21.4 ▲
Somewhat like water in the pipes seeking a common level (for which the pressures at equal elevations are the same), the thermometer and its immediate surroundings reach a common temperature (at which the average kinetic energy per particle is the same for both).

21.4 Internal Energy

In addition to the translational kinetic energy of jostling molecules in a substance, there is energy in other forms. There is rotational kinetic energy of molecules and kinetic energy due to internal movements of atoms within molecules. There is also potential energy due to the forces between molecules. The grand total of all energies inside a substance is called **internal energy.** A substance does not contain heat—it contains internal energy.

When a substance takes in or gives off heat, any of these energies may change. Thus, as a substance absorbs heat, this energy may or may not make the molecules jostle faster. In some cases, as when ice is melting, a substance absorbs heat without an increase in temperature. The substance changes phase, the subject of Chapter 23.

21.5 Measurement of Heat

So we see that heat is energy transferred from one substance to another by a temperature difference. The amount of heat transferred can be determined by measuring the temperature change of a known mass of water that absorbs the heat.

When a substance absorbs heat, the resulting temperature change depends on more than just the mass of the substance. The quantity of heat that brings a cupful of soup to a boil might raise the temperature of a pot of soup by only a few degrees. To quantify heat, we must specify the *mass* and *kind* of substance affected.

The unit of heat is defined as the heat necessary to produce some standard, agreed-on temperature change for a specified mass of material. The most commonly used unit for heat is the **calorie.** The calorie is defined as the amount of heat required to raise the temperature of 1 gram of water by 1°C.

The **kilocalorie** is 1000 calories (the heat required to raise the temperature of 1 kilogram of water by 1°C). The heat unit used in rating foods is actually a kilocalorie, although it's often referred to as the calorie. To distinguish it from the smaller calorie, the food unit is sometimes called a Calorie (written with a capital C).

It is important to remember that the calorie and Calorie are units of energy. These names are historical carryovers from the early idea that heat was an invisible fluid called *caloric.* We now know heat is a form of energy. The United States is in a period of transition to the International System of Units (SI), where quantity of heat is measured in joules, the SI unit for all forms of energy. The relationship between calories and joules is that 1 calorie equals 4.184 J. In this book we'll learn about heat with the conceptually simpler calorie—but in the lab you may use the joule equivalent, where an input of 4.184 joules raises the temperature of 1 gram of water by 1°C.*

Important Terms

calorie
kilocalorie

The calorie is a convenient heat unit because it makes the specific heat of water numerically equal to 1. It is commonly employed in chemistry courses and by chemists. Your students' next science course may use the joule for the heat unit, in which case the calorie is a stepping stone to SI. You can teach in calories or joules, or both.

A fun and impressive demonstration of the energy in food is to spear a walnut meat onto a paper clip, and ignite it. It will quickly boil 50 mL of water.

Review the joule (Chapter 8).

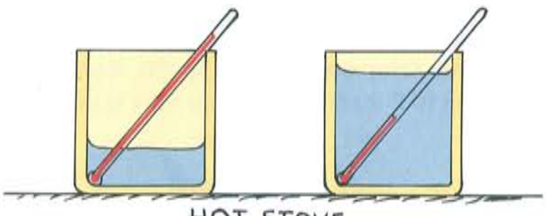


Figure 21.5
Although the same quantity of heat is added to both containers, the temperature of the container with the smaller amount of water increases more.

The energy value in food is determined by burning the food and measuring the energy that is released as heat. Food and other fuels are rated by how much energy a certain mass of the fuel gives off as heat when burned.

* Still another unit of heat is the British thermal unit (Btu). The Btu is defined as the quantity of heat required to change the temperature of 1 pound of water by 1°F. One Btu is equal to 1054 J.

Figure 21.6 ▲
To the weight watcher, the peanut contains 10 Calories; to the physicist, it releases 10 000 calories (or 41 840 joules) of energy when burned or digested.

Computational Example: Dimensional Analysis

A woman with an average diet consumes and expends about 2000 Calories per day. The energy used by her body is eventually given off as heat. How many joules per second does her body give off? Or, in other words, what is her average thermal power output?

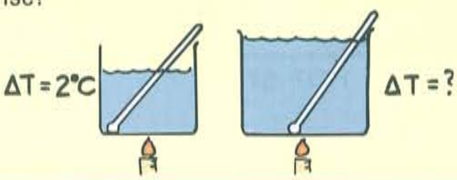
We find this by converting 2000 Calories per day to joules per second. We use the information that 1 Calorie = 4187 joules, 1 day = 24 hours, and 1 hour = 3600 seconds. The conversion is then set up as follows:

$$\frac{2000\ \cancel{\text{Cal}}}{1\ \cancel{\text{d}}} \times \frac{1\ \cancel{\text{d}}}{24\ \cancel{\text{h}}} \times \frac{1\ \cancel{\text{h}}}{3600\ \text{s}} \times \frac{4184\ \text{J}}{1\ \cancel{\text{Cal}}} = 96.8\ \text{J/s} = 96.8\ \text{W}$$

Notice that the original quantity (2000 Cal/d) is multiplied by a set of fractions in which the numerator equals the denominator. Since each fraction has the value 1, multiplying by it does not change the value of the original quantity. The rule for choosing which quantity to put in the numerator is that the units should cancel and reduce to those of the end result. (We call this technique "dimensional analysis.") So, on the average, the woman emits heat at the rate of 96.8 J/s, which is 96.8 watts. This is nearly the same as a glowing 100-W lamp! It's easy to see why a crowded room soon becomes warm! (Don't confuse the 96.8 watts given off by the woman with her internal temperature of 98.6°F. The closeness of the numerical values is a coincidence. A body's temperature and its rate of expending heat are entirely different from each other.)

Question

Suppose you use a flame to add a certain quantity of heat to 1 liter of water, and the water temperature rises by 2°C. If you add the same quantity of heat to 2 liters of water, by how much will its temperature rise?



Answer

Its temperature will rise by 1°C, because there are twice as many molecules in 2 liters of water and each molecule receives only half as much energy on average. So average kinetic energy, and temperature, increases by half as much.

21.6 Specific Heat Capacity

Important Term

specific heat capacity

Almost everyone has noticed that some foods remain hot much longer than others. Boiled onions and moist squash on a hot dish, for example, are often too hot to eat while mashed potatoes may be just right. The filling of hot apple pie can burn your tongue while the crust will not, even when the pie has just been taken out of the oven. The aluminum covering on a frozen dinner can be peeled off with your bare fingers as soon as it is removed from the oven. (But be careful of the food beneath it!)

Different substances have different capacities for storing internal energy. If we heat a pot of water on a stove, we may find that it requires 15 minutes to raise it from room temperature to its boiling temperature. But if we were to put an equal mass of iron on the same flame, we would find that it would rise through the same temperature range in only about 2 minutes. For silver, the time would be less than a minute. We find that specific materials require specific quantities of heat to raise the temperature of a given mass of the material by a specified number of degrees.

Figure 21.7 ▲
You can touch the aluminum pan of the frozen dinner soon after it has been taken from the hot oven, but you'll burn your fingers if you touch the food it contains.

Absorbed energy can affect substances in different ways. Absorbed energy that increases the translational speed of molecules is responsible for increases in temperature. Absorbed energy may also increase the rotation of molecules, increase the internal vibrations within molecules, or stretch intermolecular bonds and be stored as potential energy. These kinds of energy, however, are not measures of temperature. Temperature is a measure only of the kinetic energy of translational motion. Generally, only part of the energy absorbed by a substance raises its temperature.

Whereas a gram of water requires 1 calorie of energy to raise the temperature 1°C, it takes only about one eighth as much energy to raise the temperature of a gram of iron by the same amount. Iron atoms in the iron lattice primarily shake back and forth in translational fashion, while water molecules soak up a lot of energy in rotations, internal vibrations, and bond stretching. So water absorbs more heat per gram than iron for the same change in temperature. We say water has a higher **specific heat capacity** (sometimes simply called *specific heat*).

"Heat capacity" is sometimes used for heat per degree of a total sample (i.e., specific heat capacity times mass). "Specific heat" is an alternate expression for specific heat capacity.

Show a few numerical examples of $Q = mc\Delta T$.

Relate cooking to the physics involved. A good book on this subject is *Kitchen Science* by Howard Hillman, Houghton Mifflin, 1981.

Question

Which has a higher specific heat capacity—water or sand?

Answer

Water has a greater heat capacity than sand. Water is much slower to warm in the hot sun and slower to cool in the cold night. Water has more thermal inertia. Sand's low heat capacity, as evidenced by how quickly the surface warms in the morning sun and how quickly it cools at night, affects local climates.

The specific heat capacity of any substance is defined as the quantity of heat required to raise the temperature of a unit mass of the substance by 1 degree.

We can think of specific heat capacity as thermal inertia. Recall that *inertia* is a term used in mechanics to signify the resistance of an object to change in its state of motion. Specific heat capacity is like a thermal inertia since it signifies the resistance of a substance to change in its temperature.

Computational Example: Heating Water

When we know the specific heat capacity c for a particular substance, the quantity of heat Q involved when the mass m of the substance undergoes a temperature change ΔT is $Q = mc\Delta T$. In words, heat transferred = mass × specific heat capacity × temperature change.

Suppose we wish to know the number of calories needed to raise the temperature of 1 liter of water by 15°C. The specific heat capacity for water, c, is 1 cal/g°C, and the mass of 1 liter of water is 1 kilogram, which is 1000 grams. Since c is expressed in calories per *gram* °C, we express the mass of water m in grams. Then,

$$Q = mc\Delta T$$

$$Q = (1000\text{ g})(1\text{ cal/g°C})(15°\text{C}) = 15\,000\text{ calories}$$

Suppose we deliver this energy to the water with a 1000-watt immersion heater. How long will it take to heat the water? We know that 1000 watts delivers energy at the rate 1000 joules per second. Converting calories to joules,

$$15\,000\text{ cal} \times 4.184\text{ J/cal} = 62\,760\text{ joules}$$

At the rate of 1000 joules per second, can you see that the time required for heating the water by 15°C is somewhat more than a minute?

21.7 The High Specific Heat Capacity of Water

Water has a much higher capacity for storing energy than most common materials. A relatively small amount of water absorbs a great deal of heat for a correspondingly small temperature rise. Because of this, water is a very useful cooling agent, and is used in cooling systems in automobiles and other engines. If a liquid of lower specific heat capacity were used in cooling systems, its temperature would rise higher for a comparable absorption of heat. (Of course, if the

temperature of the liquid rises to the temperature of the engine, no further cooling will take place.) Water also takes longer to cool, a useful fact to your great-grandparents, who on cold winter nights likely used foot-warming hot-water bottles in their beds.

This property of water to resist changes in temperature improves the climate in many places. The next time you are looking at a world globe, notice the high latitude of Europe. If water did not have a high heat capacity, the countries of Europe would be as cold as the northeastern regions of Canada, for both Europe and Canada get about the same amount of the sun's energy per square kilometer. The Atlantic current known as the Gulf Stream brings warm water northeast from the Caribbean. It holds much of its internal energy long enough to reach the North Atlantic off the coast of Europe, where it then cools. The energy released (one calorie per degree for each gram of water that cools) is carried by the westerly winds over the European continent.

Similarly, the climates differ on the east and west coasts of North America. The winds in the latitudes of North America are westerly. On the west coast, air moves from the Pacific Ocean to the land. Because of water's high heat capacity, ocean temperature does not vary much from summer to winter. The water is warmer than the air in the winter, and cooler than the air in the summer. In winter, the water warms the air that moves over it and warms the western coastal regions of North America. In summer, the water cools the air and the western coastal regions are cooled. On the east coast, air moves from the land to the Atlantic Ocean. Land, with a lower specific heat capacity, gets hot in summer but cools rapidly in winter. As a result of water's high heat capacity and the wind directions, the west coast city of San Francisco is warmer in the winter and cooler in the summer than the east coast city of Washington, D.C., which is at about the same latitude.

The central interior of a large continent usually experiences extremes of temperature. For example, the high summer and low winter temperatures common in Manitoba and the Dakotas are largely due to the absence of large bodies of water. Europeans, islanders, and people living near ocean air currents should be glad that water has such a high specific heat capacity. San Franciscans are!

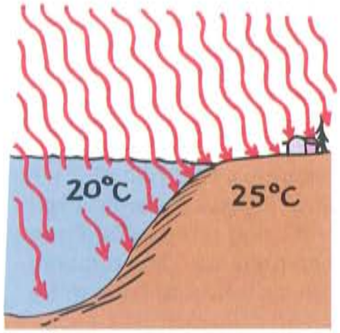


Figure 21.8 ▲
Water has a high specific heat and is transparent, so it takes more energy to heat up than land does. Why would its transparency be a factor?

Compare the very different climates of west coast San Francisco, inland St. Louis, and east coast Washington, D.C.—all about the same latitude.

Because of the moderating influence of water (net energy emitter when warmer than air; net absorber when cooler than air), islands have the most stable climates. In the continental U.S., the city having the most stable climate is San Francisco. Its island type climate is due to San Francisco being nearly surrounded by water.

21.8 Thermal Expansion

Important Terms

bimetallic strip
thermostat

When the temperature of a substance is increased, its molecules jiggle faster and normally tend to move farther apart. This results in an *expansion* of the substance. With few exceptions, all forms of matter—solids, liquids, and gases—expand when they are heated and contract when they are cooled. For comparable pressures and comparable changes in temperature, gases generally expand or contract much more than liquids, and liquids expand or contract more than solids.*

* This rule is valid if the solid, liquid, and gas expand against constant pressure. A gas in a container can be prevented from expanding, but then its pressure is not constant.

Note the importance of not filling a gasoline tank to the top. As gasoline expands in warm weather, overflow is a safety hazard and wastes money.

Ask how a thermometer would differ if glass expanded with increasing temperature more than mercury. (The temperature scale would have to be scaled downward!)

The uncommonly tiny expansion of heat-resistant glass is crucial for the mirrors in large telescopes. If the expansion were large, the mirror would lose its parabolic shape and produce a distorted image.

If concrete sidewalks and highway paving were laid down in one continuous piece, cracks would appear due to the expansion and contraction brought about by the difference between summer and winter temperatures. To prevent this, the surface is laid in small sections, each one being separated from the next by a small gap that is filled in with a substance such as tar. On a hot summer day, expansion often squeezes this material out of the joints.

The *expansion* of materials must be allowed for in the construction of structures and devices of all kinds. A dentist uses filling material that has the same rate of expansion as teeth. The aluminum pistons of an automobile engine are smaller enough in diameter than the steel cylinders to allow for the much greater expansion rate of aluminum. A civil engineer uses steel of the same expansion rate as concrete for reinforcing concrete. Long steel bridges often have one end fixed while the other rests on rockers that allow for expansion. The roadway itself is segmented with tongue-and-groove-type gaps called expansion joints (Figure 21.9).

Figure 21.9 ▲
This gap is called an *expansion joint,* and allows the bridge to expand and contract.

The Best From Conceptual Physics Alive!

Demo: Thermal Expansion

Side 3
Chapter 2

The Best From Conceptual Physics Alive!

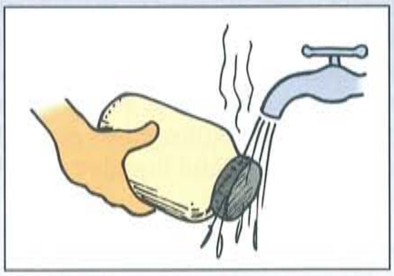
Demo: How a Thermostat Works

Side 3
Chapter 3

DOING PHYSICS

Brains Over Brawn

The next time you find it difficult to unscrew a metal lid from a jar, let thermal expansion assist you. Heat the metal lid by placing it in a stream of hot water, or momentarily placing it on a hot stove. The metal lid will expand more than the glass. Presto! Can you see why a slight twist then opens the jar? Can you explain why this works? What's the physics here?



Activity

Different materials expand at different rates. In a **bimetallic strip,** two strips of different metals, say one of brass and the other of iron, are welded or riveted together (Figure 21.10). When the strip is heated, the difference in the amounts of expansion of brass and iron shows up easily. One side of the double strip becomes longer than the other, causing the strip to bend into a curve. On the other hand, when the strip is cooled, it bends in the opposite direction, because the metal that expands the most also contracts the most. The movement of the strip may be used to turn a pointer, regulate a valve, or operate a switch.

A **thermostat** is a practical application of a bimetallic strip (Figure 21.11). The back-and-forth bending of the bimetallic coil opens and closes an electric circuit. When the room becomes too cold, the coil bends toward the brass side, and in so doing it closes an electric switch that turns on the heat. When the room becomes too warm, the coil bends toward the iron side, which opens the switch and turns off the heating unit. Refrigerators are equipped with special thermostats to prevent them from becoming too hot or too cold. Bimetallic strips are used in oven thermometers, electric toasters, automatic chokes on carburetors, and other devices.

The amount of expansion of a substance depends on its change in temperature. If one part of a piece of glass is heated or cooled more rapidly than adjacent parts, the expansion or contraction that results may break the glass. This is especially true for thick glass. Heat-resistant glass is specially formulated to expand very little with increasing temperature.

Liquids expand appreciably with increases in temperature. When the gasoline tank of a car is filled at a gas station and the car is then parked for a while, the gasoline often overflows the tank. This occurs as the cold gasoline from the underground storage tanks warms up as it sits in the car's tank. As the gasoline warms, it expands and overflows the gas tank. Similarly, an automobile radiator filled to the brim with cold water overflows when heated.

In most cases, the expansion of liquids is greater than the expansion of solids. The gasoline overflowing a car's tank on a hot day is evidence for this. Similarly, a pot filled to the brim with water soon overflows when heated. Also, mercury rises in a thermometer when heated because the liquid mercury expands more than the glass.

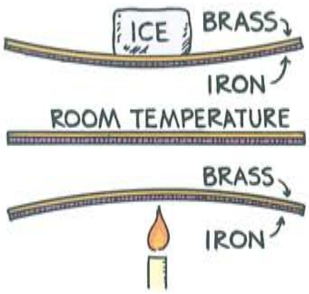


Figure 21.10 ▲
A bimetallic strip. Brass expands (or contracts) more when heated (or cooled) than does iron, so the strip bends as shown.

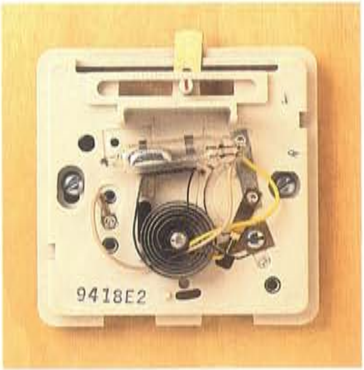


Figure 21.11 ▲
A thermostat. When the bimetallic coil expands, the mercury rolls away from the electrical contacts and breaks the circuit. When the coil contracts, the mercury rolls against the contacts and completes the electric circuit.

Figure 21.12 ▲
Place a dented Ping-Pong ball in boiling water, and you'll remove the dent. Why?

Question

Why is it advisable to allow telephone lines to sag when stringing them between poles in summer?

Answer

Telephone lines are longer in summer, when they are warmer, and shorter in winter, when they are cooler. They therefore sag more on hot summer days than in winter. If the telephone lines are not strung with enough sag in summer, they might contract too much and snap during the winter.

Computational Example: Ratio and Proportion

Steel changes in length about 1 part in 100 000 for each Celsius degree change in temperature. This is a *ratio*,

$$\frac{1}{100\,000}$$

For different lengths of steel, expansion would follow the same proportion. For short lengths of steel, expansion may be negligible. But consider the expansion of a make-believe snugly fitting steel pipe that completely encircles the earth. How much longer would this 40-million-meter pipe be if its temperature increased by 1°C?

The ratio of its change in length X to its full size is the same as the ratio above, so for a 1°C temperature change we say

$$\frac{1}{100\,000} = \frac{X\,\text{m}}{40\,000\,000\ \text{m}}$$

A little computation will show that the change in length X is 400 m. Here's the interesting part: If such a pipe were elongated by this 400 m, then there would be a gap between it and the earth's surface. Would the gap be big enough to put this book under? To crawl under? To drive a truck under? How big would this gap be?

We can find the gap by ratio and proportion. The ratio of circumference C to diameter D for any circle is equal to π (about 3.14). The ratio of the change in circumference ΔC to the change in diameter ΔD also has the same value. Inserting values, we have

$$\frac{\Delta C}{\Delta D} = \frac{400\ \text{m}}{\Delta D} = 3.14$$

Solving for ΔD gives

$$\Delta D = \frac{400\ \text{m}}{3.14} = 127.4\ \text{m}$$

This 127.4 m is the increase in *diameter* of the circular pipe. The size of the gap between the earth's surface and the expanded pipe is equal to the increase in radius, which is half the increase in diameter, or 63.7 m.

So if a steel pipe that fits snugly against the earth were increased in temperature by 1°C, perhaps by people all along its length breathing hard on it, the pipe would expand and stand an amazing 63.7 meters off the ground! Using ratio and proportion is a straightforward way to solve many problems. Another way to solve for the expansion of a material involves a formula ($L = \alpha L_0 \Delta T$). You may encounter this formula in the lab part of your course, but we'll not treat it here in the text.

21.9 Expansion of Water

Almost all liquids will expand when they are heated. Ice-cold water, however, does just the opposite! Water at the temperature of melting ice, 0°C (or 32°F), *contracts* when the temperature is increased. This is most unusual. As the water is heated and its temperature rises, it continues to contract until it reaches a temperature of 4°C. With further increase in temperature, the water then begins to *expand;* the expansion continues all the way to the boiling point, 100°C. This odd behavior is shown graphically in Figure 21.13.

Bismuth and antimony are two other substances that expand upon solidifying. Because of this property, these metals are used in the lead of printers' type. When pure lead solidifies, shrinkage occurs, distorting the mold. The addition of bismuth or antimony counteracts the shrinkage.

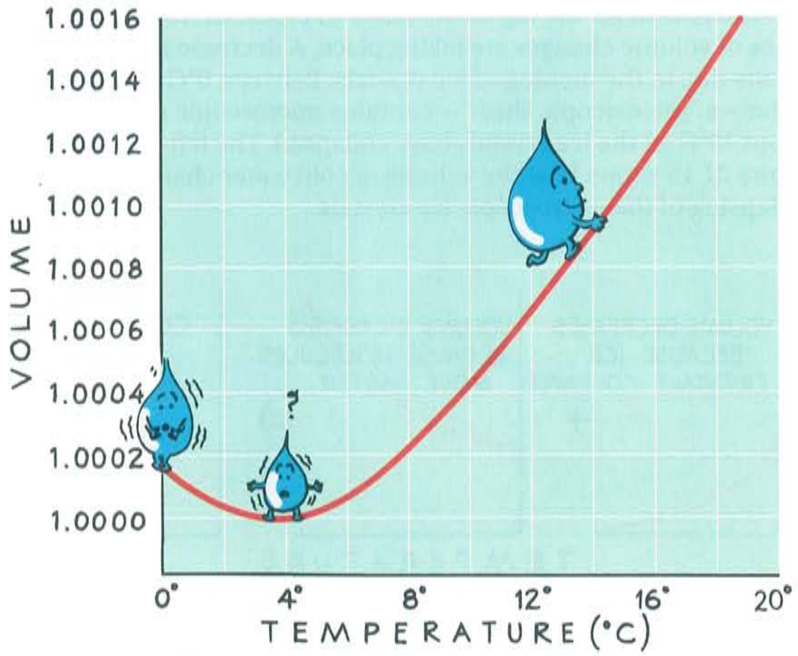
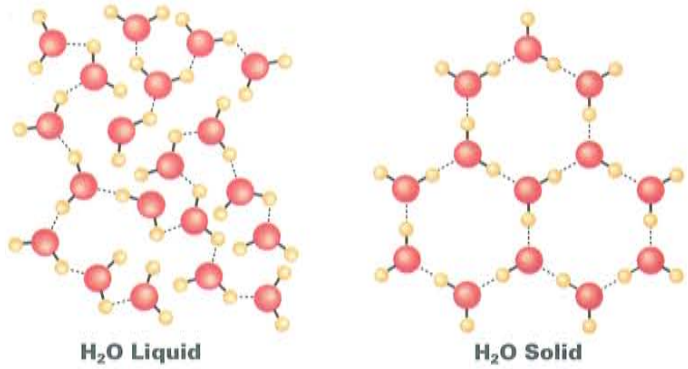


Figure 21.13 ▲
The change in volume of water with increasing temperature.

A given amount of water has its smallest volume—and thus its greatest density—at 4°C. The same amount of water has its largest volume—and smallest density—in its solid form, ice. (Remember, ice floats in water, so it must be less dense than water.) The volume of ice at 0°C is not shown in Figure 21.13. (If it were plotted to the same exaggerated scale, the graph would extend far beyond the top of the page.) After water has turned to ice, further cooling causes it to contract.

The explanation for this behavior of water has to do with the odd crystal structure of ice. The crystals of most solids are structured so that the solid state occupies a smaller volume than the liquid state. Ice, however, has open-structured crystals (Figure 21.14). These crystals result from the angular shape of the water molecules, plus the fact that the forces binding water molecules together are strongest at certain angles. Water molecules in this open structure occupy a greater volume than they do in the liquid state. Consequently, ice is less dense than water.

Figure 21.14 ▶
Water molecules in their crystal form have an open-structured, six-sided arrangement. As a result, water expands upon freezing, and ice is less dense than water.



The reason for the dip in the curve of Figure 21.13 is that two types of volume changes are taking place. A decrease in volume occurs due to the melting of ice crystals. Between 0°C and 10°C, water—a "microscopic slush"—contains microscopic ice crystals. At about 10°C all the ice crystals have collapsed. The left-hand graph in Figure 21.15 shows how the volume of cold water changes due to the collapsing of the microscopic ice crystals.

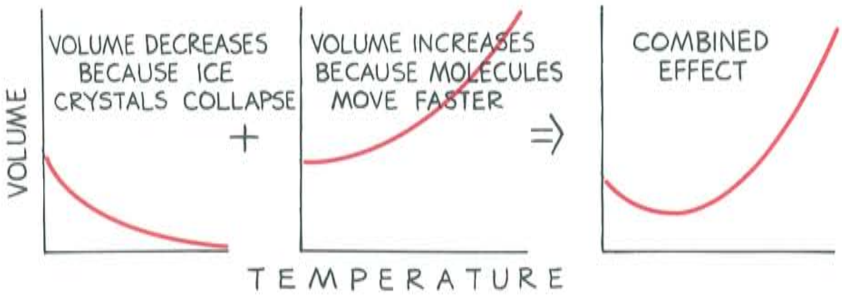


Figure 21.15 ▲
The collapsing of ice crystals (left) plus increased molecular motion with increasing temperature (center) combine to make water most dense at 4°C (right).

While crystals are collapsing as the temperature increases between 0°C and 10°C, increased molecular motion results in expansion. This effect is shown in the center graph in Figure 21.15. Whether ice crystals are in the water or not, increased vibrational motion of the molecules increases the volume of the water.

When we combine the effects of contraction and expansion, the curve looks like the right-hand graph in Figure 21.15 (or Figure 21.13). This behavior of water is of great importance in nature. Suppose that the greatest density of water were at its freezing point, as is true of most liquids. Then the coldest water would settle to the bottom, and ponds would freeze from the bottom up. Pond organisms would then be destroyed in winter months. Fortunately, this does not happen. The densest water, which settles at the bottom of a

pond, is 4 degrees above the freezing temperature. Water at the freezing point, 0°C, is less dense and "floats," so ice forms at the surface while the pond remains liquid below the ice.

Let's examine this in more detail. Most of the cooling in a pond takes place at its surface, when the surface air is colder than the water. As the surface water is cooled, it becomes denser and sinks to the bottom. Water will "float" at the surface for further cooling only if it is as dense or less dense than the water below.

Consider a pond that is initially at, say, 10°C. It cannot possibly be cooled to 0°C without first being cooled to 4°C. And water at 4°C cannot remain at the surface for further cooling unless all the water below has at least an equal density—that is, unless all the water below is at 4°C. If the water below the surface is any temperature other than 4°C, any surface water at 4°C will be denser and sink before it can be further cooled. So before any ice can form, all the water in a pond must be cooled to 4°C. Only when this condition is met can the surface water be cooled to 3°, 2°, 1°, and 0°C without sinking. Then ice can form.

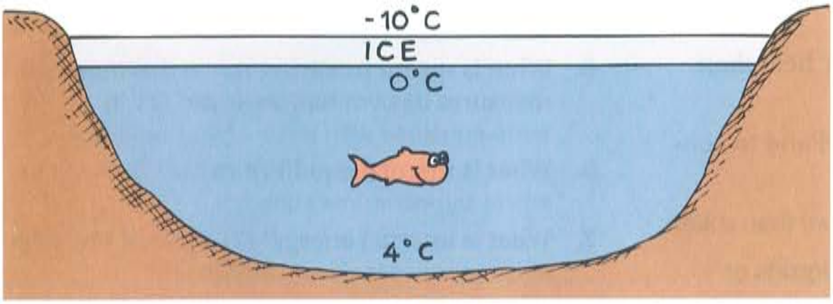


Figure 21.16 ▲
As water is cooled at the surface, it sinks until the entire lake is 4°C. Only then can the surface water cool to 0°C without sinking.

Thus, the water at the surface is first to freeze. Continued cooling of the pond results in the freezing of the water next to the ice, so a pond freezes from the surface downward. In a cold winter the ice will be thicker than in a milder winter.

Very deep bodies of water are not ice-covered even in the coldest of winters. This is because all the water in a lake must be cooled to 4°C before lower temperatures can be reached, and the winter is not long enough for all the water to be cooled to 4°C. If only some of the water is 4°C, it will lie on the bottom. Because of water's high specific heat and poor ability to conduct heat, the bottom of deep lakes in cold regions is a constant 4°C the year round. Fish should be glad that this is so.

21 Chapter Review

For fuller explanations, see the TE notes in the front of this book.

Concept Summary

Temperature is the measurement that tells how warm or cold something is.

- Temperature is directly proportional to the average translational kinetic energy of the molecules within an ideal gas.

Heat is energy that transfers between two things due to a temperature difference.

- Matter does not contain heat; rather, it contains internal energy.

Specific heat is a measure of how much heat is required to raise the temperature of a unit mass of a substance by one degree.

- Water has a much higher specific heat than other common substances.

Matter tends to expand when heated and to contract when cooled.

- Liquids usually expand slightly more than solids.
- Gases expand much more than liquids or solids for comparable increases in temperature (and comparable pressure).
- Water is highly unusual in that it contracts as it warms from 0°C to 4°C and its solid form (ice) is less dense than its liquid form.

Important Terms

absolute zero (21.1)
bimetallic strip (21.8)
calorie (21.5)
Celsius scale (21.1)
Fahrenheit scale (21.1)
heat (21.2)
internal energy (21.4)
Kelvin scale (21.1)
kilocalorie (21.5)
specific heat capacity (21.6)
temperature (21.1)
thermal contact (21.2)
thermal equilibrium (21.3)
thermostat (21.8)

Review Questions

Recall of key chapter ideas

1. How is temperature commonly measured? (21.1) With a thermometer
2. How many degrees are between the melting point of ice and boiling point of water on the Celsius scale? Fahrenheit scale? (21.1) 100; 180
3. Why is it incorrect to say that matter *contains* heat? (21.2) Contains internal energy, heat is energy flow due to ΔT
4. In terms of differences in temperature between objects in thermal contact, in what direction does heat flow? (21.2) From high to low temperature
5. What is meant by saying that a thermometer measures its own temperature? (21.3) Its temp equalizes with temp of surroundings
6. What is thermal equilibrium? (21.3) State where temperatures equalize
7. What is internal energy? (21.4) Grand total of all energies inside a substance
8. What is the difference between a calorie and a Calorie? (21.5) 1000 calories = 1 Calorie
9. What does it mean to say that a material has a high or low specific heat capacity? (21.6) High or low capacity to store internal energy
10. Do substances that heat up quickly normally have high or low specific heat capacities? (21.6) Low
11. How does the specific heat capacity of water compare with that of other common substances? (21.7) High
12. Why is the North American west coast warmer in winter months and cooler in summer months than the east coast? (21.7) Winds westerly, ocean gives/absorbs int eng
13. Why does a bimetallic strip curve when it is heated (or cooled)? (21.8) One side expands (or contracts) more than other
14. Which expands most for increases in temperature: solids, liquids, or gases? (21.8) Gases

15. At what temperature is the density of water greatest? (21.9) 4°C

16. Ice is less dense than water because of its open crystalline structure. But why is water at 0°C less dense than water at 4°C? (21.9) Because of presence of "microscopic slush"

17. Why do lakes and ponds freeze from the top down rather than from the bottom up? (21.9) Ice water and ice float at surface

18. Why do shallow lakes freeze quickly in winter, and deep lakes not at all? (21.9) All water must first be cooled to 4°C

Plug and Chug

Math reinforcement—conceptual development through applied problem solving

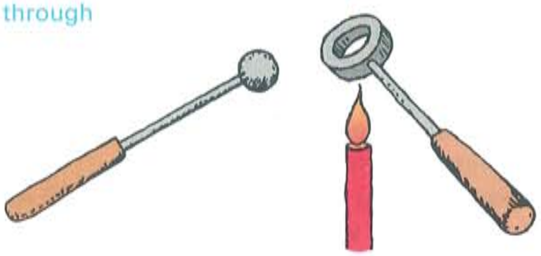
Heat transfer in calories is given by $Q = mc\Delta T$, where m is mass in grams, c is specific heat capacity in cal/g°C, and ΔT is in °C.

1. Calculate the number of calories of heat needed to change 500 grams of water by 50 Celsius degrees. $Q = mc\Delta T = (500\text{ g})(1\text{ cal/g°C})(50°\text{C}) = 25\,000\text{ cal}$
2. Calculate the number of calories given off by 500 grams of water cooling from 50°C to 20°C. $Q = mc\Delta T = (500\text{ g})(1\text{ cal/g°C})(30°\text{C}) = 15\,000\text{ cal}$
3. A 30-gram piece of iron is heated to 100°C and then dropped into cool water where the iron's temperature drops to 30°C. How many calories does it lose to the water? (The specific heat capacity of iron is 0.11 cal/g°C.) $Q = mc\Delta T = (30\text{ g})(0.11\text{ cal/g°C})(70°\text{C}) = 231\text{ cal}$
4. Suppose the same 30-gram piece of iron is dropped into another container of water and gives off 165 calories in cooling. Calculate the iron's temperature change. $\Delta T = Q/mc = 165\text{ cal}/(30\text{ g})(0.11\text{ cal/g°C}) = 50°\text{C}$
5. What mass of water will give up 240 calories when its temperature drops from 80°C to 68°C? $m = Q/c\Delta T = 240\text{ cal}/(1.0\text{ cal/g°C})(12°\text{C}) = 20\text{ g}$
6. When a 50-gram piece of aluminum at 100°C is placed in water, it loses 735 calories of heat while cooling to 30°C. Calculate the specific heat capacity of the aluminum. $c = Q/m\Delta T = 735\text{ cal}/(50\text{ g})(70°\text{C}) = 0.21\text{ cal/g°C}$

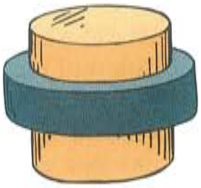
Think and Explain

Conceptual development through applied critical thinking

1. If you drop a hot rock into a pail of water, the temperature of the rock and the water will change until both are equal. The rock will cool and the water will warm. Does the same principle hold true if the rock is dropped into a large lake? Explain. Yes, though lake will have negligible increase in temp
2. If you stake out a plot of land with a steel tape measure using map measurements on a very hot day, will you enclose more or less land than your measurements indicate? More land; steel expands
3. A metal ball is just able to pass through a metal ring. When the ball is heated, thermal expansion will not allow it to pass through the ring. What would happen if the ring, rather than the ball, were heated? Would the ball pass through the heated ring? Does the size of the hole in the ring increase, decrease, or stay the same? Hole expands to let ball through



4. A snugly fitting steel pipe circling the world would stand about 64 meters off the ground if its temperature were increased by 1°C. What would be the result if the pipe were instead cooled by 1°C? Would squeeze about 64 m inward on world
5. After a machinist slips a hot, snugly fitting iron ring over a cold brass cylinder, the ring becomes "locked" in position and can't be removed even by subsequent heating. This procedure is called "shrink fitting." How does it occur? Can you conclude anything about the thermal expansion rates of iron and brass? Ring shrinks, brass expands at least as much as iron



6. If you take a bite of hot pizza, the sauce may burn your mouth while the crust, at the same temperature, will not. Explain. Sauce has a higher c than the crust

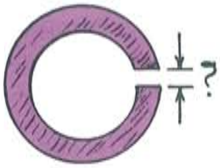
7. In the old days, on a cold winter night it was common to bring a hot object to bed with you. Which would be better—a 10-kilogram iron brick or a 10-kilogram jug of hot water at the same temperature? Explain. Hot water, because more internal energy

8. On a hot day you remove from a picnic cooler a chilled watermelon and some chilled sandwiches. Which will remain cooler for a longer time? Why? Watermelon; high c of water

9. Iceland, so named to discourage conquest by expanding empires, is not at all ice-covered like Greenland and parts of Siberia, even though it is nearly on the Arctic Circle. The average winter temperature of Iceland is considerably higher than regions at the same latitude in eastern Greenland and central Siberia. Why is this so? Iceland is warmed by cooling surrounding water.

10. Why is it important to protect water pipes so they don't freeze? Water expands when freezes and breaks pipes.

11. Suppose you cut a small gap in a metal ring, as shown. If you heat the ring, will the gap become wider or narrower? Wider, same as if gap were filled with metal



12. Would a bimetallic strip function if the two different metals happened to have the same rates of expansion? Is it important that they expand at different rates? Explain. No; yes; one side must become longer to bend other

13. State whether water at the following temperatures will expand or contract when warmed: 0°C; 4°C; 6°C. Contract; expand; expand

14. In addition to the overall motion of a molecule that is associated with temperature, some molecules can absorb large amounts of energy in the form of internal vibrations and rotations of the molecule itself. Would you expect materials composed of such molecules to have a high or a low specific heat capacity? Why? High spec heat because more ways to store energy

15. If water had a lower specific heat capacity, would lakes be more likely or less likely to freeze in the winter? More likely

Think and Solve

Math reinforcement—variable substitution and equation solving

1. If you wished to warm 100 kg of water by 15°C for your bath, how much heat would be required? (Give your answer in calories and joules.) $Q = mc\Delta T = (100\text{ kg})(1\text{ cal/g°C})(15°\text{C}) = 1500\text{ kcal} = 6276\text{ kJ}$

2. What would be the final temperature if you mixed a liter of 20°C water with 2 liters of 40°C water? $Q_{lost} = Q_{gained}$, $mc(T - 20°\text{C}) = 2mc(40°\text{C} - T)$, $T = 33.3°\text{C}$

3. What would be the final temperature if you mixed a liter of 40°C water with 2 liters of 20°C water? $mc(40°\text{C} - T) = 2mc(T - 20°\text{C})$, $T = 26.7°\text{C}$

4. What is the specific heat capacity of a 50-gram piece of 100°C metal that will change 400 grams of 20°C water to 22°C? $c = Q/m\Delta T = 0.2\text{ cal/g°C}$

5. Suppose that a metal bar 1 m long expands 0.5 cm when it is heated. How much would it expand if it were 100 m long? $(0.5)/(1) = (\Delta L)/(100)$, $\Delta L = 50\text{ cm}$

6. Steel expands 1 part in 100 000 for each 1°C increase in temperature. If the 1.5-km main span of a steel suspension bridge had no expansion joints, how much longer would it be for a temperature increase of 20°C? $\Delta L = \alpha L_0 \Delta T = (10^{-5})(1.5\text{ km})(20°\text{C}) = 3 \times 10^{-4}\text{ km} = 30\text{ cm}$